Ozone Modeling and Assimilation for Numerical Weather Prediction

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<u>Introduction:</u> What is the role of ozone in NWP?

<u>Modeling:</u> How to model ozone for NWP?

<u>Impact:</u> Does 3-D prognostic ozone improve forecasts?

<u>Future:</u> Is there a role for SO data in NWP?

How does ozone influence NWP?

1. Radiative Effect

– Ozone is a radiatively active gas that interacts with both the solar (SW) and terrestrial (LW) radiation. Improved modeling of ozone will improve ozone radiative heating/cooling.

Ozone radiative effect

$$\frac{d\mathbf{v}}{dt} = -\alpha\nabla p - \nabla\phi + \mathbf{F} - 2\Omega\times\mathbf{v}$$

Conservation of momentum

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\mathbf{v})$$

Conservation of mass

$$p\alpha = RT$$

Equation of state

Ozone heating

$$C_p\frac{dT}{dt} - \alpha\frac{dp}{dt} = \boxed{Q}$$

Conservation of energy

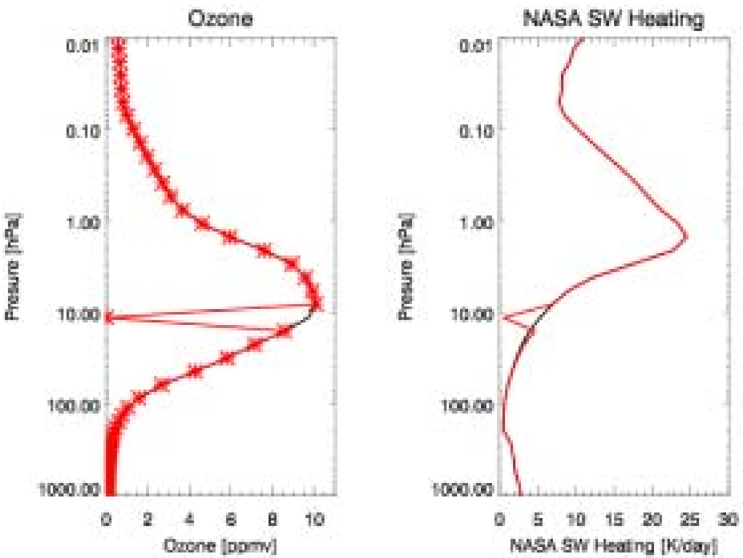
$$\frac{\partial\rho q}{\partial t} = -\nabla\cdot(\rho\mathbf{v}q) + \rho(E-C)$$

Conservation of moisture

Ozone heating/cooling converts radiation energy into thermal energy or vice-versa.

SW radiative heating

Using the Chou and Suarez scheme



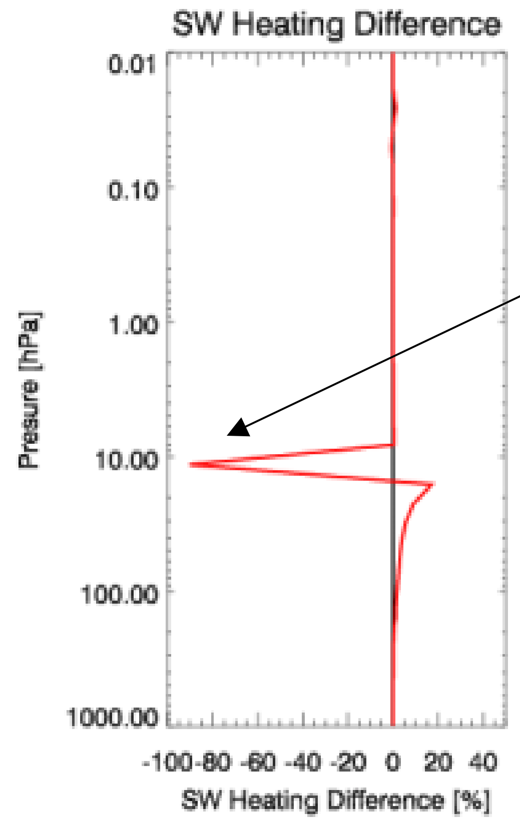
O3scle = -1.00000

SZA = 0.00000

Surface temp = 294

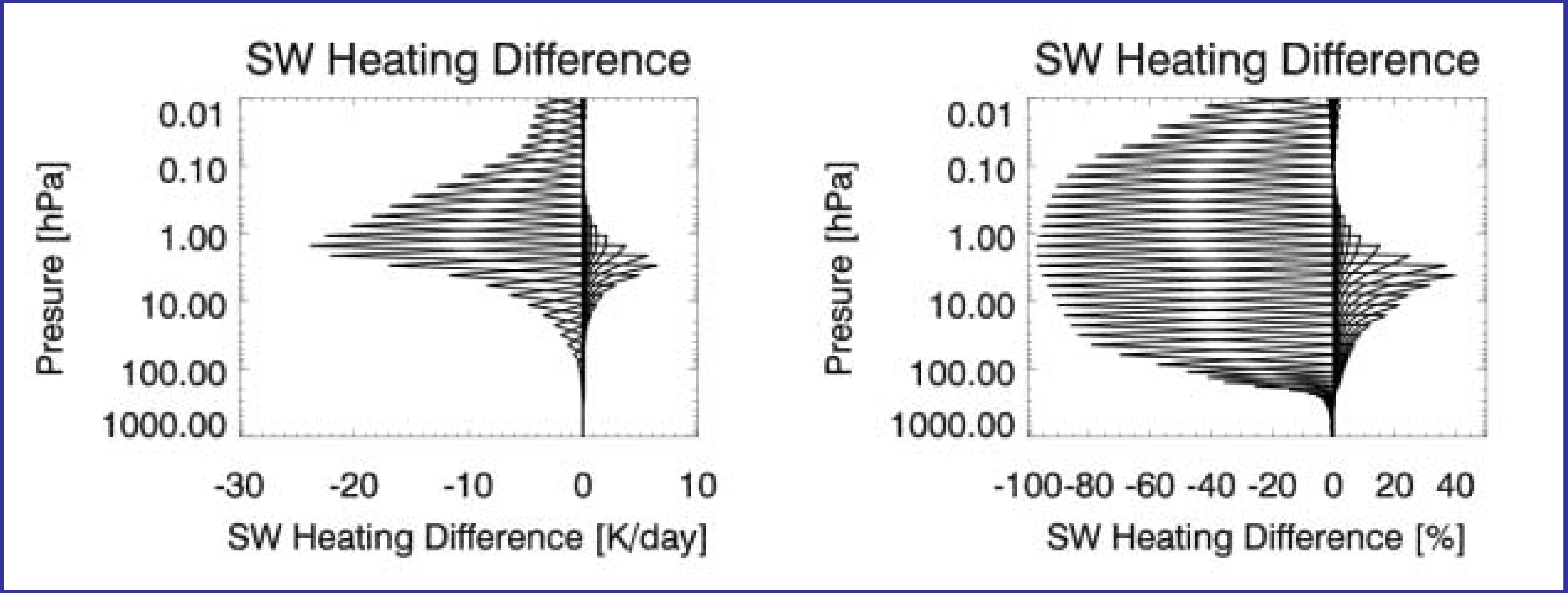
Albedo = 0.2

CO_2 = 350.000



Heating rate changes by 90% at 10 mb when ozone changes by 100%.

SW heating differences for 100% ozone decrease at SZA=0



Sensitivity of SW heating due to ozone changes increases with altitude to a maximum near 1.0 hPa. Very small sensitivity below about 500 hPa.

How does ozone influence NWP?

1. Radiative Effect
   – Ozone is a radiatively active gas that interacts with both the solar (SW) and terrestrial (LW) radiation. Improved modeling of ozone will improve ozone radiative heating/cooling.
2. Assimilation of Satellite Radiances
   – NWP centers are moving towards assimilation of radiances rather than the retrieved quantities.
   – Ozone plays an important role in the assimilation of radiances from certain IR instruments (e.g., HIRS, AIRS). Better ozone profiles → better radiance assimilation → better initial conditions → better forecasts.

Ozone influence on radiance assimilation

Brightness temperature calculated from Met Office model background fields.

HIRS → High Resolution Infrared Radiation Sounder

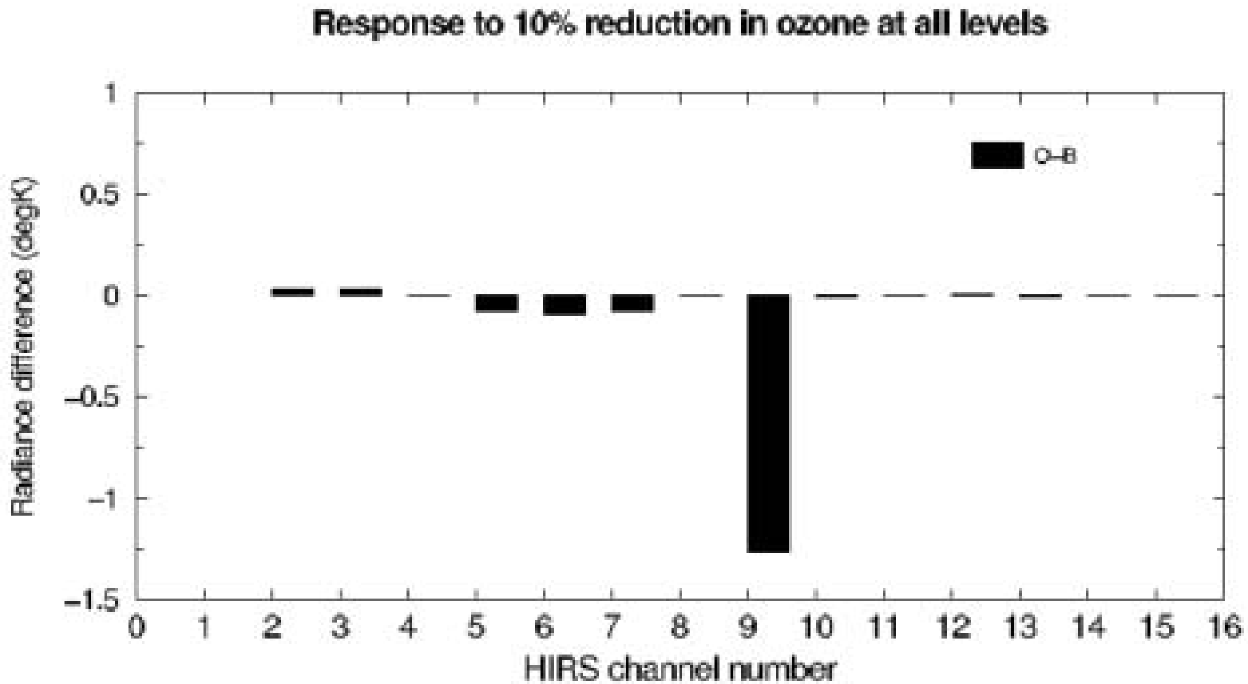


Figure 1: Response of HIRS brightness temperature to a 10 % reduction in ozone at all levels

From Jackson and Saunders, Met Office Forecasting Research Technical Report No. 394

Modeling Ozone → new transport equation

$$\frac{d\mathbf{v}}{dt} = -\alpha\nabla p - \nabla\phi + \mathbf{F} - 2\Omega\times\mathbf{v}$$

Conservation of momentum

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\mathbf{v})$$

Conservation of mass

$$p\alpha = RT$$

Equation of state

Ozone heating

$$C_p\frac{dT}{dt} - \alpha\frac{dp}{dt} = \boxed{Q}$$

Conservation of energy

$$\frac{\partial\rho q}{\partial t} = -\nabla\cdot(\rho\mathbf{v}q) + \rho(E-C)$$

Conservation of moisture

$$\frac{dO_3}{dt} = S(O_3)$$

Coupling prognostic ozone with radiation

Conservation of ozone

Ozone photochemistry in NWP models

- Reasonable simulations of stratospheric ozone photochemistry require **at least** 40 different minor chemical species and 60 different chemical reactions.

→ **Full O_3 chemistry runs are not currently computationally practical for ops**

First approach: Use net Prod/Loss from a full-chemistry 2-D (zonal mean) model where Prod/Loss of ozone mixing ratio depends on latitude/pressure/time.

Second approach: Similar, but allow Prod/Loss to depend on additional factors: temperature, ozone concentration, and overhead ozone column. → **CD86 (Cariolle and Déqué, 1986)**, **LINOZ (McLinden et al., 2000).**

Future Approaches [In development]:

- Cold tracer algorithm to simulate *heterogeneous* ozone hole chemistry.
- Improved parameterization based on output from NRL-CHEM2D model with full chemistry and radiation from 0-100 km

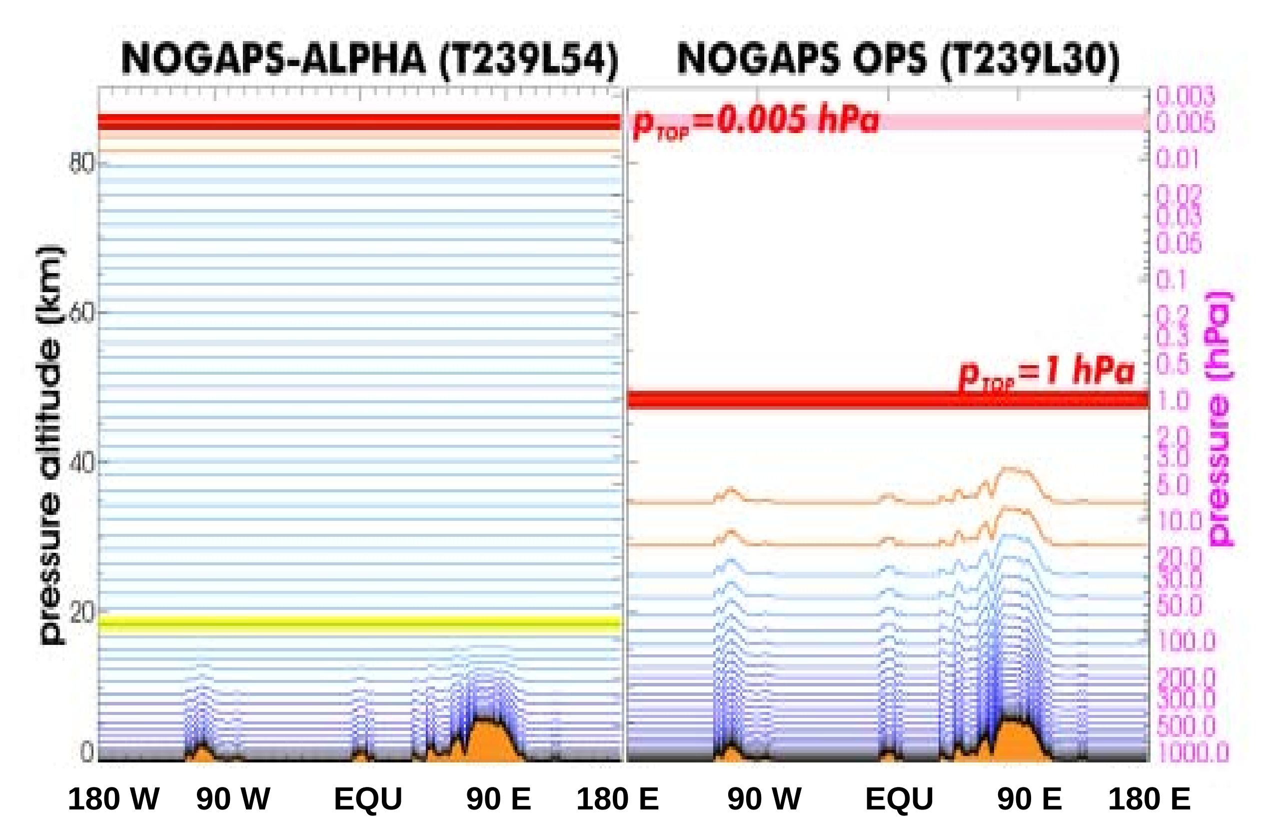
Ozone Photochemistry and Coupling at Various Centers

Center	Homogen. (gas phase) Chemistry	Heterogen. (solid/liquid) Chemistry	Coupled with Radiation?	Used in Radiance Assimilation?	Data Assimilated In development
NCEP	Prod/Loss from GSFC 2D CTM	None	Yes	Yes	**SBUV/2**
GMAO Tropospheric chemistry in development.	Prod/Loss from GSFC 2D CTM	Cold tracer (in development)	No	No	**SBUV/2, TOMS, MLS, MIPAS, POAM**
ECMWF	Cariolle and Déqué (1986)	• Chlorine term • Cold tracer (in development	No	Yes	**SBUV/2, MIPAS, GOME**
NRL-ops	Currently uses 2D ozone climatology				
NRL-ALPHA	• NRL CHEM2D • Cariolle and Déqué(1986) • LINOZ	• Chlorine term and cold tracer (in development)	Yes	No	**SBUV/2, NPP OMPS**

Ozone Forecasting with NOGAPS-ALPHA

NOGAPS → Navy Operational Global Atmospheric Prediction System

Model level cross-sections at 34.5 N



New Research Version of the Navy's Operational NWP model → NOGAPS-ALPHA.

Result of 4-year Navy-funded effort, jointly with NRL-DC and NRL-Monterey.

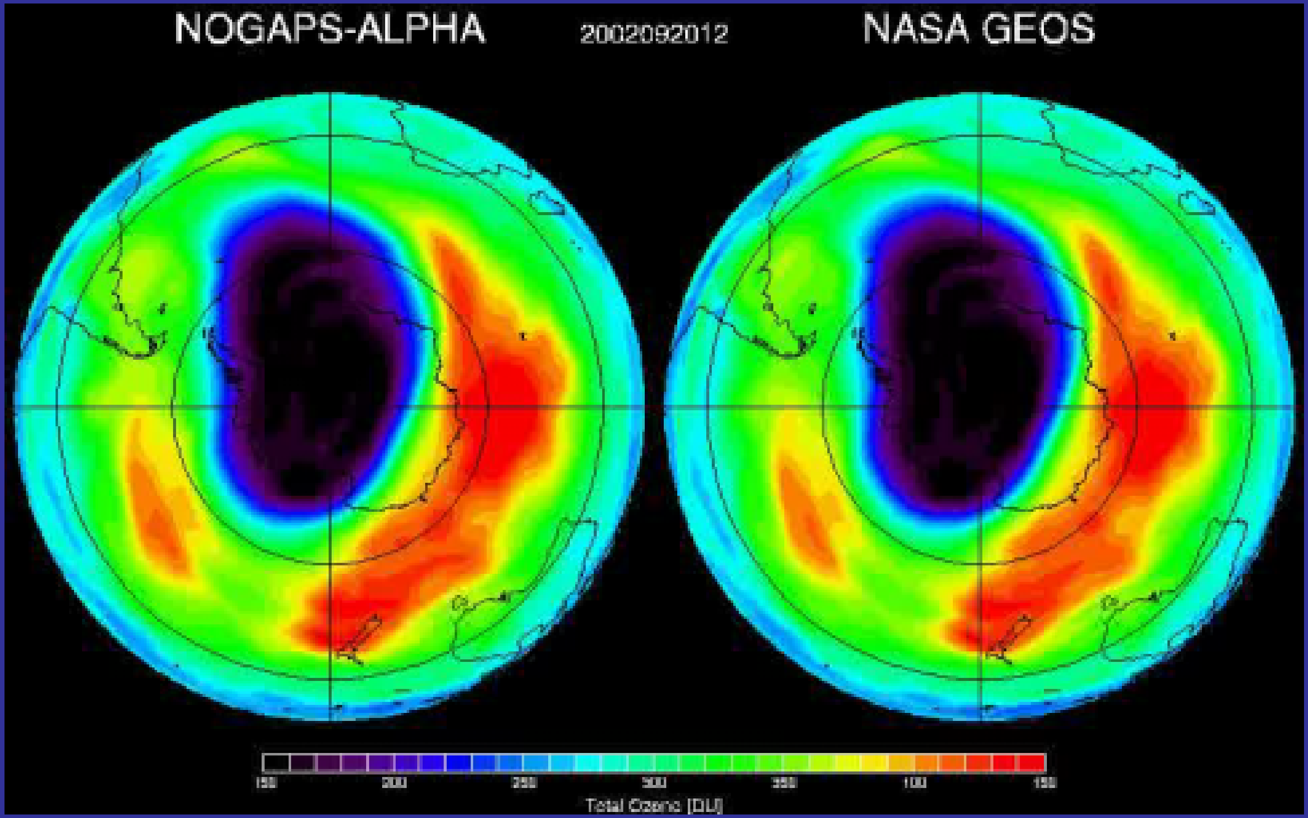
<u>New Physics Packages</u>

- **New upper-level gravity-wave drag**
- **New radiation scheme**
- **New hybrid σ-p vertical coordinate**
- **New upper-level meteorological initialization**
- **Top raised to 0.005 hPa (z~85 km)**
- **New 3D prognostic chemistry capabilities**

NOGAPS-ALPHA total ozone forecast

20 September – 10 October 2002

NOGAPS-ALPHA Forecast **GMAO Assimilation**

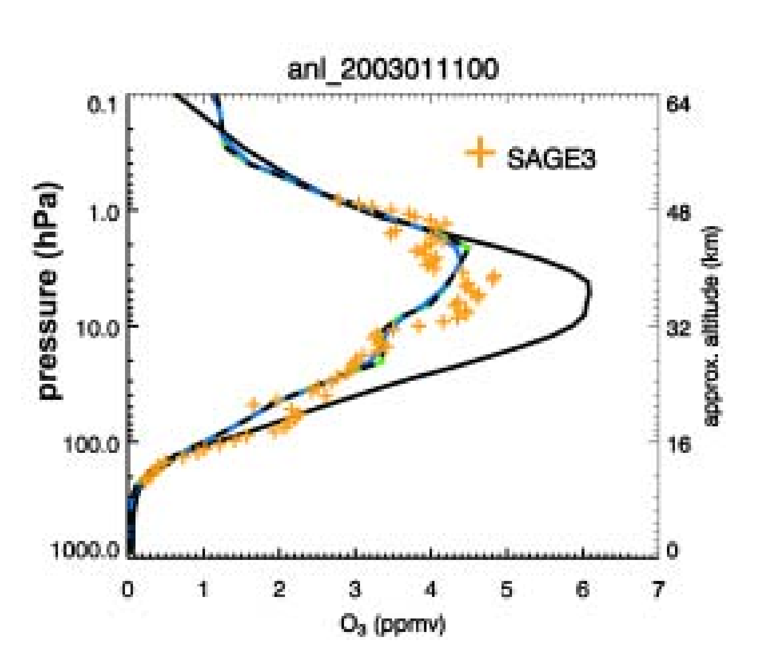


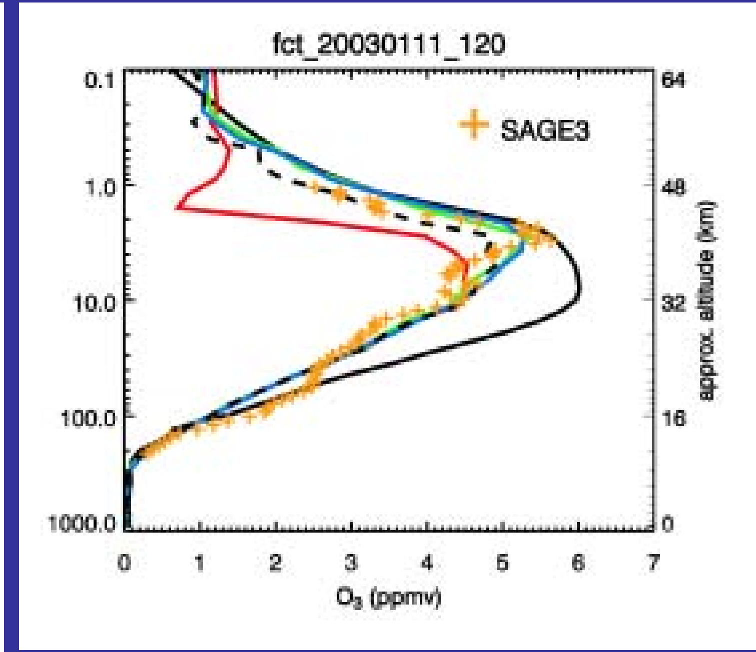
20-day forecast of the 2002 SH major warming.

Initialized with NASA-GEOS ozone assimilation.

Ozone chemistry based on Cariolle and Deque (1986)

NOGAPS-ALPHA forecasts during SOLVE2





Profiles over Kiruna, Sweden

T511 ECMWF Forecast

Passive O_3 (*dashed*)

NRL CHEM2D

UC-Irvine LINOZ

Cariolle-Déqué

Initialization on 11 January

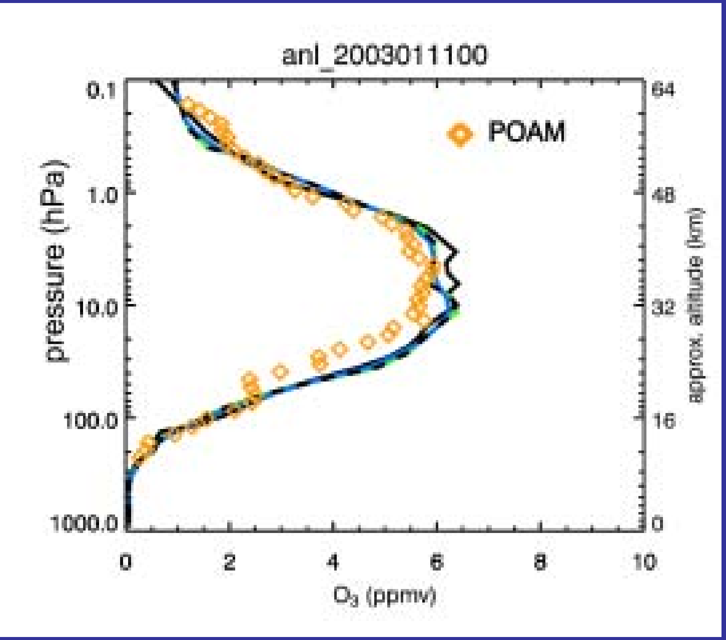
- Use GEOS ozone assimilation for NOGAPS-ALPHA initialization.
- Note large difference between GEOS and ECMWF.

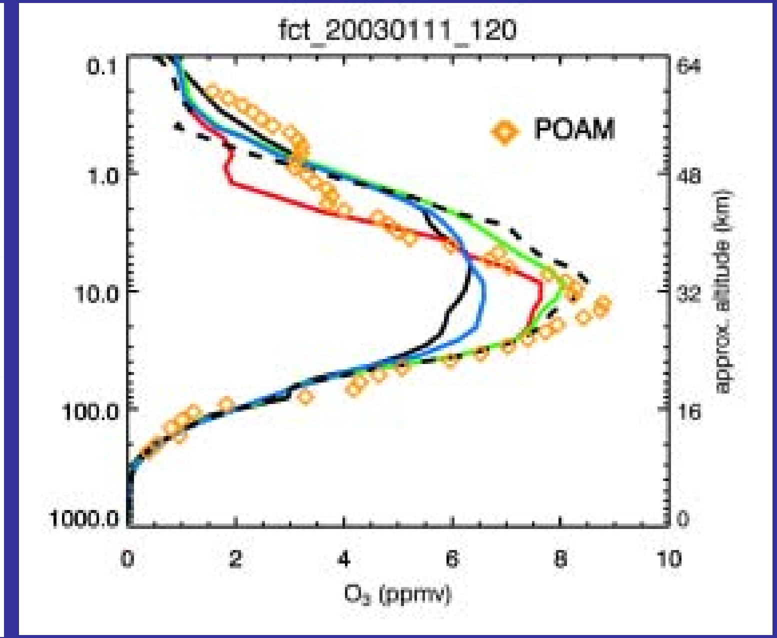
5-day forecast

- LINOZ scheme has excessive loss in upper stratosphere.
- All schemes close to passive ozone in lower stratosphere.
- ECMWF forecast too high→ due to poor initial field.

Results from McCormack et al., submitted paper, 2004.

NOGAPS-ALPHA forecasts during SOLVE2





Profiles over Siberia (65 N, 135 E)

T511 ECMWF Forecast

Passive O_3 (*dashed*)

NRL CHEM2D

UC-Irvine LINOZ

Cariolle-Déqué

Initialization on 11 January

- Here GEOS and ECWMF analyses are very similar.
- Good agreement with POAM data at initialization.

5-day forecast

- LINOZ scheme still has excessive loss in upper stratosphere.
- ECMWF scheme is too low → photochemistry too rapid in the lower stratosphere → too tightly constrained to the climatology.
- Air from lower sunlit latitudes was brought poleward during this period.

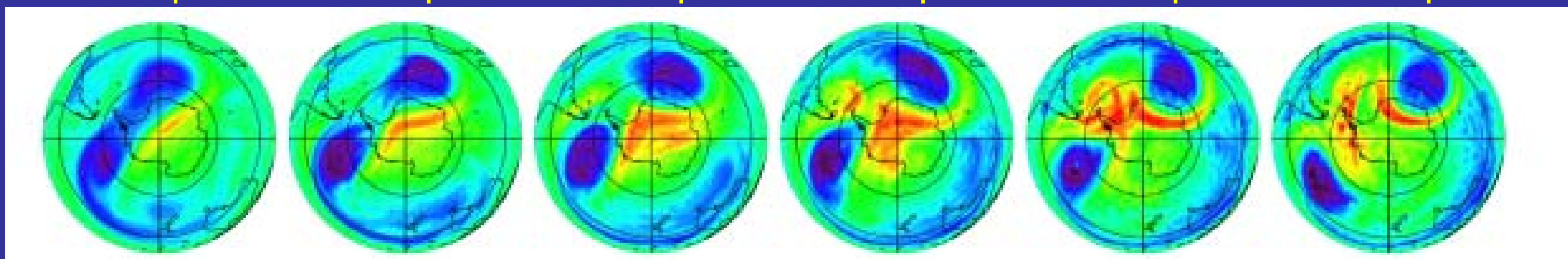
Results from McCormack et al., submitted paper, 2004.

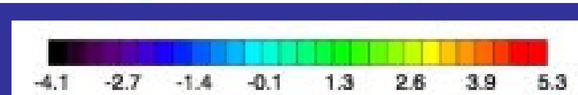
Radiative effects of prognostic ozone

5-day forecast ozone and temp differences at 10 hPa

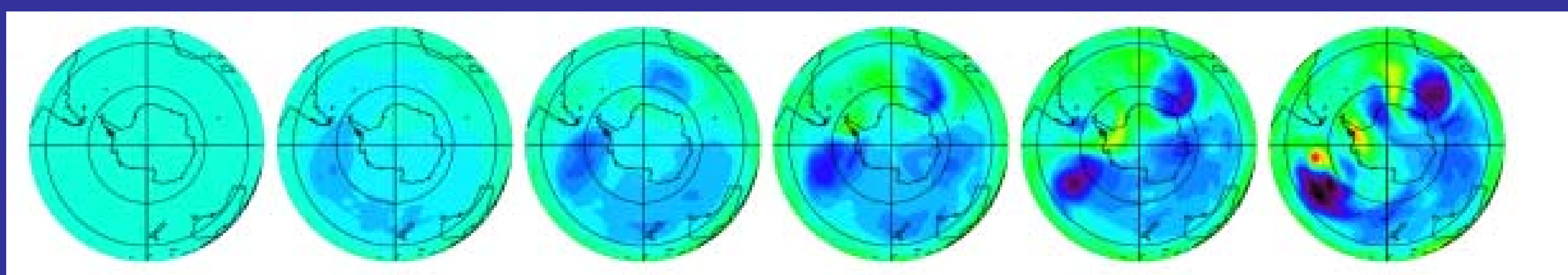
Difference between 3-D prognostic ozone and operational 2-D ozone for 5-day forecast

23 Sept | 24 Sept | 25 Sept | 26 Sept | 27 Sept | 28 Sept





Ozone Difference (ppmv) at 10 mb (~32 km)



Temperature Difference (K) at 10 mb (~32 km)

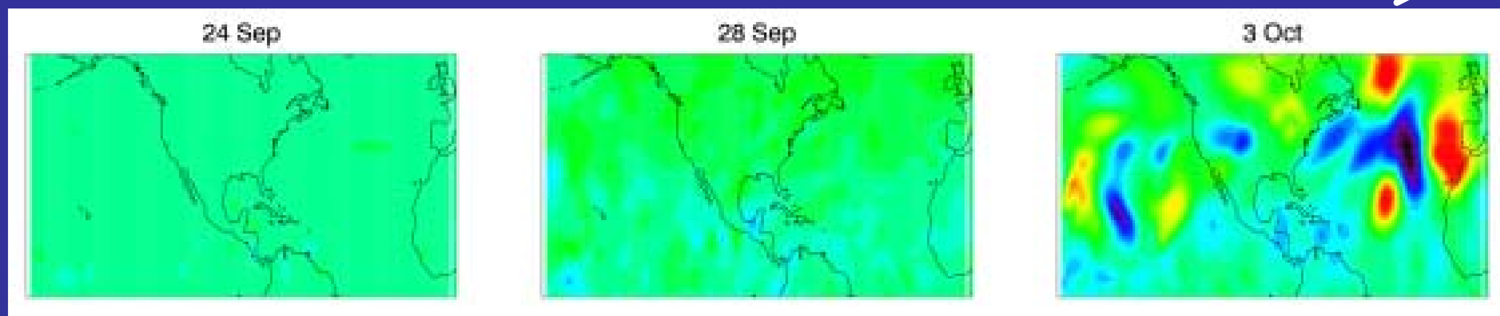
Temperature differences of up to 2.7 K over 5 days

Effects of Prognostic ozone at 100 hPa

1-day **5-day** **10-day**

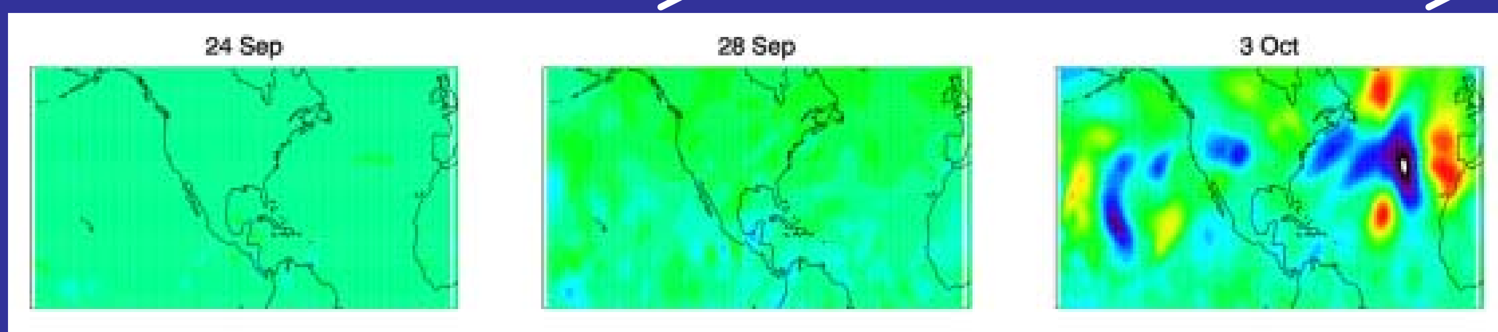
3-D ozone used throughout

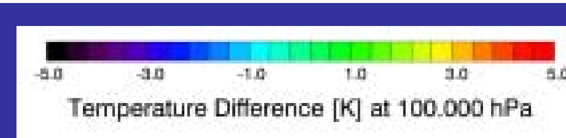
Temperature difference for runs with 3-D versus 2-D ozone



3-D ozone **2-D ozone**

Small temperature perturbations that developed over the first 5 days grow rapidly out to day 10.



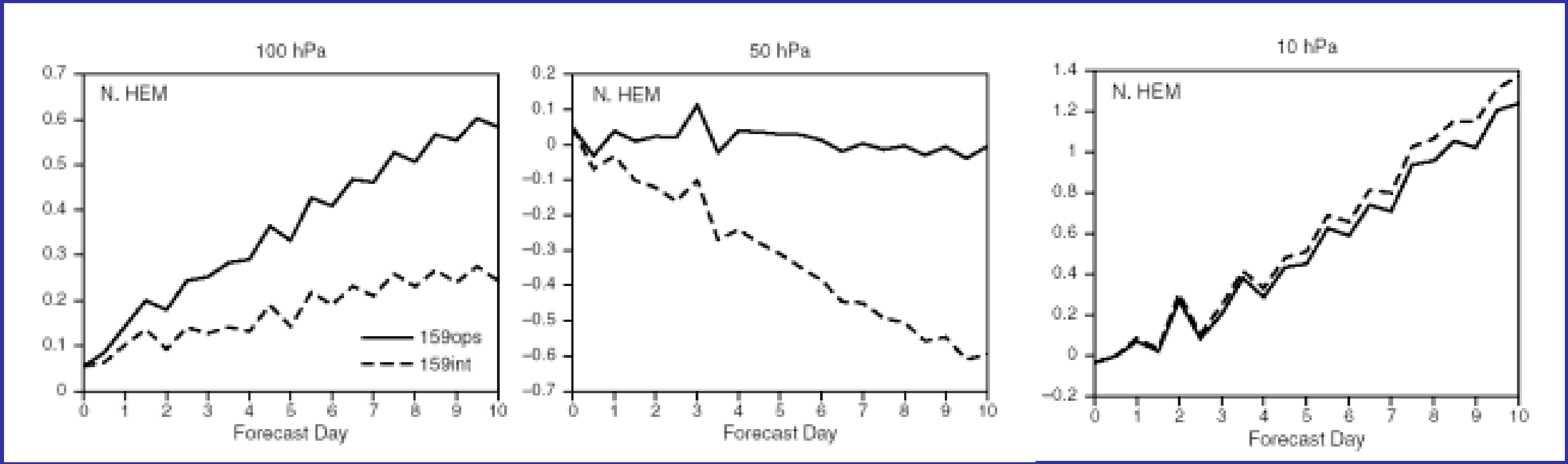


Does realistic ozone modeling improve NWP forecast skill?

- Few quantitative results are available.
  - Problems
    - It is computationally expensive to test effects of model changes on forecast skill (long-term mean statistics).
    - The small changes induced by altering the ozone may have a significant impact on individual unstable situations. However, the impact on long-term mean statistics may be small.
  - Results
    - ECMWF has documented the effects of coupling their ozone with radiation (only at pressure levels 100-10 hPa).
    - No results available for traditional forecast skill (500 hPa anomaly correlations, etc.)
    - NRL has done preliminary calculations.

Effects of ozone on forecast skill
ECMWF results from forecasts during Jan-Mar 1992

NH Mean Temperature error (Jan-Mar 1992)



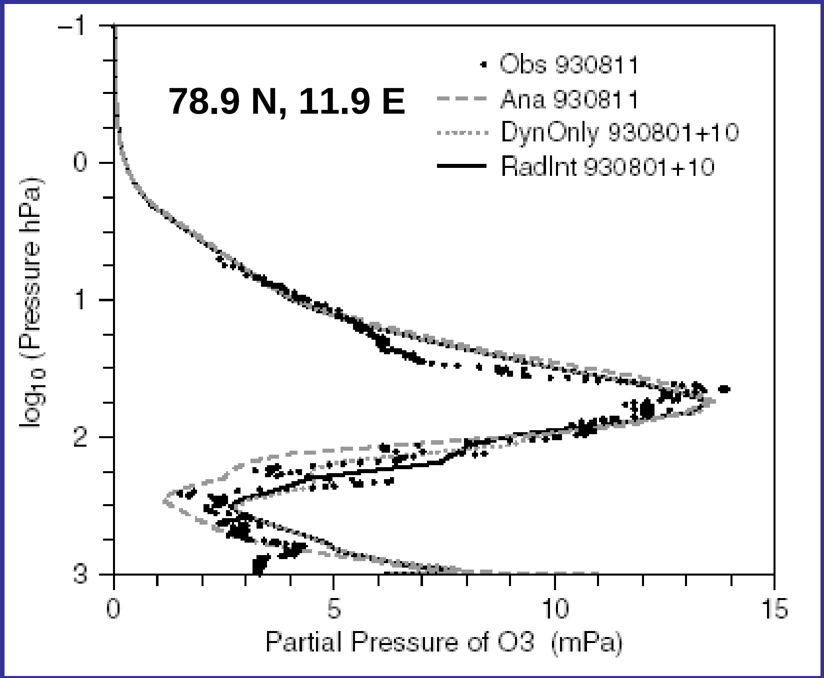
- **10-day forecasts show that coupling 3-D ozone with radiation causes systematic cooling of all areas (NH, tropics, SH) at 100 and 50 hPa and a systematic heating at 10 hPa and higher.**
- **Whether this is a positive impact on forecast skill greatly varies.**

Results from Morcrette, “Ozone-radiation interactions in the ECMWF forecast system, ECMEF Tech. Memo #375, Dec. 2003.

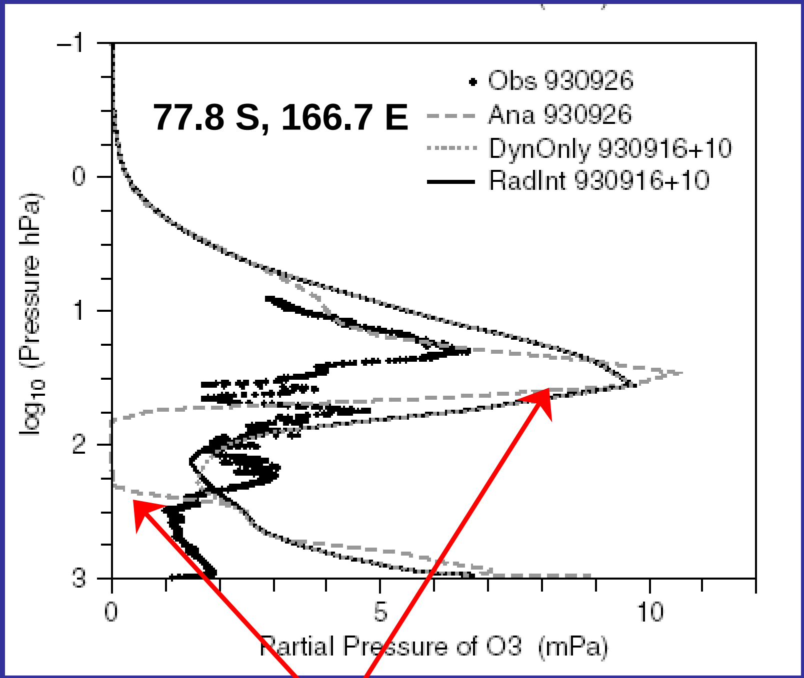
Effects of ozone on forecast skill

ECMWF results from forecasts during Aug-Oct 1992

Ny Alesund, 11 Aug 1993



McMurdo, 26 Sept 1993



ECMWF analysis does pretty well if the observed profile is unimodal.

However, the analysis is unable to handle complicated structure. This is likely due to both lack of observations with high vertical resolution and errors in the specified vertical structure function.

Results from Morcrette, “Ozone-radiation interactions in the ECMWF forecast system, ECMEF Tech. Memo #375, Dec. 2003.

What is the future role of SO data in NWP?

- Validation
  - Both of assimilated and forecast ozone
- Off-line assimilation
  - e.g., NASA GEOS re-analyzed ozone
- Operational assimilation?
  - Need data in near real time
  - Need to be able to assimilate sparse data sets.
- Preparation for assimilation of future data
  - Development of simulated high-resolution ozone profiles to help in preparation for assimilation of NPP OMPS.

Summary

- **Ozone can affect NWP via**
  - Direct radiative effect
  - Influence on satellite radiance assimilation
- **Ozone modeling and assimilation challenges**
  - Assimilation of data in NRT from multiple instruments
  - Realistic parameterized ozone photochemistry
- **Ozone effects on model forecast skill**
  - Few assessments done to date, results are ambiguous
- **Role of SO data in NWP**
  - Provides critical vertical resolution, yet limited coverage presents challenges for operational assimilation.